FINAL REPORT
ON TASK ORDER 7

EVALUATION OF THE PERFORMANCE OF SEVEN REFRACTORY METAL THERMOCOUPLES

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA
(CONTRACT NAS 8-5196)

SOUTHERN RESEARCH INSTITUTE
2000 9th Avenue S. Birmingham 5, Alabama

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Southern Research Institute
Birmingham, Alabama
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SUMMARY

Seven refractory metal thermocouples were calibrated under this program. The thermocouples were made of tungsten or tungsten-rhenium alloys. Five thermocouples were manufactured by Auto-Control Laboratories (ACL), Los Angeles, California; two were manufactured by Space Sciences, Incorporated.

The calibrations were performed in an inductively heated tungsten blackbody cavity and in an oxy-acetylene flame. The evaluations included studies of the effect of immersion depth on thermocouple response time and maximum emf output. On two of the ACL assemblies, several calibrations revealed data scatter of approximately 25 percent. The scatter was attributed mainly to a shorting effect caused by the central wire contacting the outer sheath at more than one location as suggested by post mortem X-rays of two assemblies. Some scatter was attributed to emf instability. Two "second generation" ACL assemblies exhibited more consistent behavior; X-rays of these couples did not reveal multiple junctions.

One SSI thermocouple failed on the initial exposure at 3950°F. The second SSI thermocouple had an open circuit and could not be calibrated.

INTRODUCTION

This is the final report covering the work performed under Task Order 7 of Contract No. NAS8-5196. The contract involved research, development and prototype model construction of calorimeter and thermocouple assemblies designed toward the Saturn and C-1 environment. This report deals with the calibration and evaluation of several refractory metal thermocouples supplied by Space Sciences, Inc., and by Auto Control Laboratories, Inc. The work program outlined by NASA under this task order required the calibration of one unit of each type in a blackbody cavity and the evaluation of one unit of each type when exposed to an oxy-acetylene flame.

DESCRIPTION OF THERMOCOUPLES

The thermocouples evaluated were composed of refractory metals (presumedly tungsten/tungsten-26 rhenium), with one material as a central wire and the other as a surrounding sheath. The wire and the sheath were

welded at the tip to form a junction. No information was supplied as to orientation of the materials. The thermocouples were supplied by two manufacturers, Space Sciences, Inc., and Auto Control Laboratories, Inc. Table 1 contains information concerning the physical dimensions of the thermocouples and also a summary of the evaluations performed on each.

CALIBRATION IN TUNGSTEN BLACKBODY CAVITY

Apparatus and Procedure - The thermocouples were calibrated in a blackbody cavity heated inductively in an inert atmosphere of argon. The apparatus was essentially the same as reported previously for the work under Task Order 1. Some minor modifications were made in the method of mounting the thermocouple; however, these caused no major effect on thermocouple performance.

Basically, the apparatus consisted of a tungsten cavity centered in a flat induction coil. The cavity was insulated with zirconium oxide to maintain isothermals and also to shield the copper coil from the intense radiation. A drawing of the apparatus is shown in Figure 1. Care was taken to prevent the inclusion of foreign materials into the build-up which might have caused premature failure of the thermocouples. During a run with the thermocouple in position in the cavity, it was not possible to read the temperature in the lower part of the cavity. To provide a means to monitor temperature optically, the true blackbody temperature was compared to the lip temperature of the cavity. This calibration is shown in Figure 2. A calibration check was made each time the cavity position was changed.

A reading during a calibration run consisted of the following: time; temperature on the lip of the cavity; power input to the coil; and millivolt output of the thermocouple at a 32°F reference temperature. The optical temperature readings were made with a Leeds and Northrup Type 8622 optical pyrometer and the millivolt readings were made with a Leeds and Northrup null balance potentiometer.

Data and Results - The calibrations obtained for the thermocouples in the blackbody cavity are shown in Figures 3 through 8 and in Tables 2 through 8. Of the seven thermocouples investigated, data were not obtained for two. These two were the ACL first generation couple 4735-003 and the SSI couple No. 141-10249. The SSI couple indicated an open circuit. The output of the ACL couple was extremely low and the circuit through the couple opened at 1920°F indicating an internal failure. However, an X-ray of this thermocouple failed to indicate the cause of the failure; see Figure 9.

Considerable variation in outputs was obtained between ACL couples 4735-007 and 4735-009 and also between individual runs of the same couple. To confirm the variation in output between the two assemblies, both were totally immersed in a common hot zone of a graphite furnace. Inconclusive results were obtained from the run; however, it was evident that the outputs of the two probes were not in agreement. To further verify the disagreement in the outputs, X-rays of the two thermocouples were made and are shown in Figure 10. The X-rays showed the central wire of 4735-007 to be bent and touching the inside of the sheath at a point near the tip. The central wire of probe 4735-009 was in contact with the outer cylinder for about one inch back from the probe tip and additional material was evident in the annulus of the outer cylinder for about 1/2 inch back from the tip. The wires touching the cylinders and also the additional material in the annulus of 4735-009, if electrically conductive, could have created a junction at almost any position back up the probe. Also, the location of the junction could have varied from run to run, causing the disagreement obtained during successive runs. The foreign material in the sheath would have altered the thermoelectric properties of the junction.

For the two ACL couples 4735-011 and 4735-012Z, the blackbody calibrations were in fair agreement. The maximum deviation occurred at about 2500°F and was 12.9%. The agreement also was fair as compared to the calibration supplied by ACL. All of the curves tended to converge at the higher temperatures. The output of the 4735-011 probe more closely followed the data as given by Hoskins Manufacturing Company for tungsten versus tungsten-26 rhenium.

X-rays of 4735-011 and 4735-012Z are shown in Figures 11 and 12 respectively. The central wires of these couples were straight and isolated from the sheath; however, there was additional material in the annulus of 4735-012Z near the tip. The X-rays taken after exposure revealed an apparent crack in the sheath of 4735-011 and a rough surface on 4735-012Z. Neither of the thermocouple circuits opened during the runs, although the output of 4735-012Z became erratic at the higher temperature levels in the blackbody cavity.

As mentioned previously, only one of the SSI thermocouples was evaluated. The probe evaluated (141-10253) was exposed to about 3900°F in the blackbody cavity at which point the circuit of the couple opened. No calibration data were supplied by the manufacturer, and the composition of the thermoelements was unspecified. The experimental values are plotted in Figure 8 with reference data reported by Hoskins Manufacturing Company for W/W-26 Re and W-5 Re/W-26 Re. From 1500°F, to 2750°F, the data exhibited closer agreement with the reference curve for W-5 Re/W-26 Re. Above 2750°F, the emf output fell below both curves.

TIME, TEMPERATURE AND IMMERSION DEPTH EVALUATIONS

In addition to the blackbody calibration, a study of the influence of immersion depth, time, and temperature versus millivolt output was made on thermocouple ACL 4735-007. These evaluations were made by lowering the thermocouple into the tungsten cavity, which was preheated to the desired temperature, and monitoring the output of the thermocouple relative to time.

The output was recorded versus time on a Moseley X-Y recorder. Typical results are shown in Figure 13. Measurements were made at temperatures of 2000°F, 2500°F, and 3000°F and at immersion depths of 1/2", 7/8", and 1-1/4". Recall that this couple was later shown to be faulty by X-ray; therefore, the time constants obtained from these measurements are not considered reliable due to the uncertainty in the location of the junction. However, the measurements are believed to indicate the relative effect of immersion depth on the response of the thermocouple.

The results of these evaluations are shown in Table 9 and Figures 14, 15, and 16. The maximum output from the assembly for each immersion depth was compared to results previously obtained for an immersion depth of 1-1/8 inch; see Figure 14. The emf outputs obtained for the 1/2 inch immersion depth were considerably less than for the deeper immersions. The results from the evaluations to 1-1/4 inch immersion confirmed that the assembly had been permanently damaged by the prior runs, since the output again was considerably reduced from the very first exposure.

The effect of changing the immersion depth on the equilibrium temperature is shown in Figure 15. The results show that an increased immersion depth increased the maximum output from the assembly through a depth of at least 1-1/4 inch and probably more. The depth of the cavity utilized for these evaluations limited the maximum depth to which the assembly could be immersed.

The effect of immersion depth on the length of time required for the assembly to reach a maximum output is shown in Figure 16. The time required for the assembly to produce a maximum output decreased as the immersion depth was increased, with increasing depths having progressively less effect. These results indicated that an increase in immersion depth beyond some limit would not continue to decrease the length of time required for the assembly to reach a maximum output. Of course, the time to obtain equilibrium output also would be a function of the heat flux density of the exposure. These probes should be exposed at intensities close to the use conditions to obtain precise times for response.

CALIBRATION IN OXY-ACETYLENE FLAME

Apparatus and Procedure - The apparatus used for the calibration runs in the burner exposures is shown in Figure 17. The oxygen-acetylene burner has previously been found to produce a maximum flame temperature between 4760°F and 4870°F, the melting points of molybdenum and zirconia, respectively, and a maximum heat flux density of approximately 600 $Btu/ft^2/sec$. The burner flame was preset so that the heat flux at any specified distance from the burner face would not change after the beginning of the exposure. The temperature levels at which measurements were made were controlled by varying the distance from the thermocouple to the burner face.

The temperature of the thermocouple tip was read with an optical pyrometer by viewing axially into a graphite cylinder placed approximately 3/32 inch over the tip. The cylinder formed an approximate blackbody cavity with a depth to diameter ratio of 4 to 1 so that no corrections were required to the optical pyrometer readings, and errors of no more than about 30°F could be expected from blackbody deviation. The cylinder also prevented any flames from interfering with the optical line of sight.

The output of the thermocouple was monitored with an x-y time recorder at a 32°F reference temperature. One optical temperature measurement was made at the end of each exposure cycle just prior to turning off the burner. Typical results from an exposure in the burner are shown in Figure 18.

Data and Results - The data obtained for ACL thermocouples 4735-007 and 4735-011 are given in Tables 10 and 11 and in Figures 19 and 20 respectively. For 4735-007 excellent agreement was obtained in emf output with the first runs (maximum output) in the blackbody cavity. The maximum exposure temperature was about 3500°F. After this run, it was found that the graphite cylinder had become welded to the tip of the thermocouple. In the attempt to remove the graphite cylinder the tip of the thermocouple was broken precluding any further exposures.

The broken tip from assembly No. 4735-007 was sectioned and mounted for a metallographic analysis. Figure 21 is a photomicrograph made from 50X overlays after polishing and a Nital etch (3 cc HNO_3 and 97 cc ethyl alcohol) as normally used for iron. The tungsten sheath and tungsten-26 rhenium central wire were distinguishable along with a porous material both inside and outside of the sheath. After additional polishing and a "tungsten" etch (Basic K_3 Fe[CN]$_6$), another photomicrograph was made of the probe tip using the same magnification; see Figure 22. Figure 23 shows photomicrographs of the material around the probe tip magnified 150 times after the "tungsten" etch. For the "tungsten" etch, the material outside of the

tungsten sheath appeared to be much less porous and less affected by the etchant. It appears from the selective etching that there was considerable iron in the bulb of material on the outside of the sheath.

The data obtained for 4735-011 in the burner exposure were somewhat lower than obtained in the blackbody cavity but exhibited good agreement with the calibration data supplied by ACL; see Figure 20. The deviation between the two curves was about 5.7% at 3000°F and about 5.0% at 4000°F. The maximum exposure temperature was 4510°F.

DISCUSSION

The rather wide scatter between runs on the same thermocouple was probably due in part to emf instability. Walker, Ewing and Miller[1] studied emf instability of refractory metal thermocouples up to 2000°C in vacuum and in argon. Sheathed and unsheathed thermocouples were pre-exposed at various times and temperatures. The change in emf was measured against an unexposed reference of the same thermocouple alloy at temperatures up to 1625°C (2957°F). They found that emf instability was dependent on both the time and temperature of the pre-exposure. For sheathed thermocouples some instability was due to pickup of impurities, primarily iron, from the sheath. In general any change in emf due to pickup of impurities occurred during the initial exposure to 1625°C, with no further change occurring after subsequent exposures. Most of the emf change after the initial "iron effect" was due to other internal changes in the thermoelements, including recrystallization, volatilization and phase changes.

They further reported that in the case of tungsten/tungsten-26 rhenium thermocouples, the tungsten-26 rhenium leg was the more unstable. Maximum changes in indicated temperature at 1625°C (2957°F) were 61°F, 99°F and 119°F for exposure times of 20 hours, 72 hours and 120 hours, respectively. The instability of the tungsten-26 rhenium leg increased rapidly with increasing temperature.

Referring back to our data for the ACL thermocouples, note that Figure 3 shows considerable scatter between runs in the tungsten blackbody cavity for assembly 4735-007. However, data obtained in the oxy-acetylene flame duplicated the very first calibration. Thus, the scatter was evidently not due primarily to irreversible emf instability, but may have resulted from the erratic behavior of the central wire contacting the sheath at different locations.

[1]Walker, B. E., C. T. Ewing and R. R. Miller, "Instability of Refractory Metal Thermocouples," NRL Report 6231, U. S. Naval Research Laboratory, Washington, D. C., 1965.

Recall that the X-ray of this couple (Figure 10) showed the central wire in contact with the outer cylinder. This explanation would also apply to the data for assembly 4735-009. For assembly 4735-011, the data obtained in the oxy-acetylene flame were somewhat lower than the data obtained in the blackbody cavity; see Figure 20. Since the X-ray, Figure 11, did not indicate a secondary junction, it seems likely that this couple may have suffered a slight shift in emf output.

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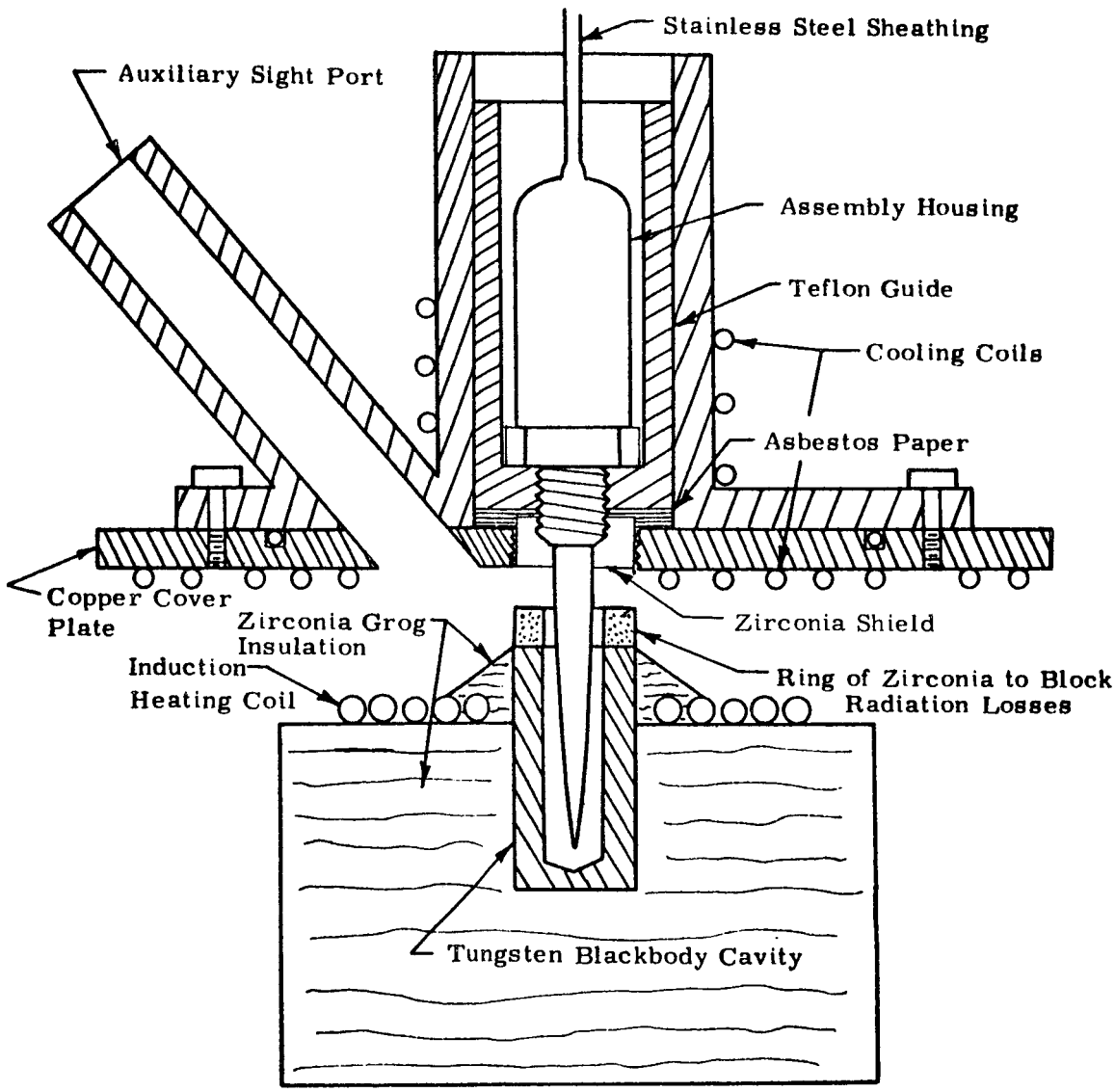


Figure 1. Sectioned View of the Mounting and Evaluation Technique Used to Evaluate High Temperature Thermocouple Assemblies Using a Teflon Guide, Asbestos Washers, and a Zirconia Shield

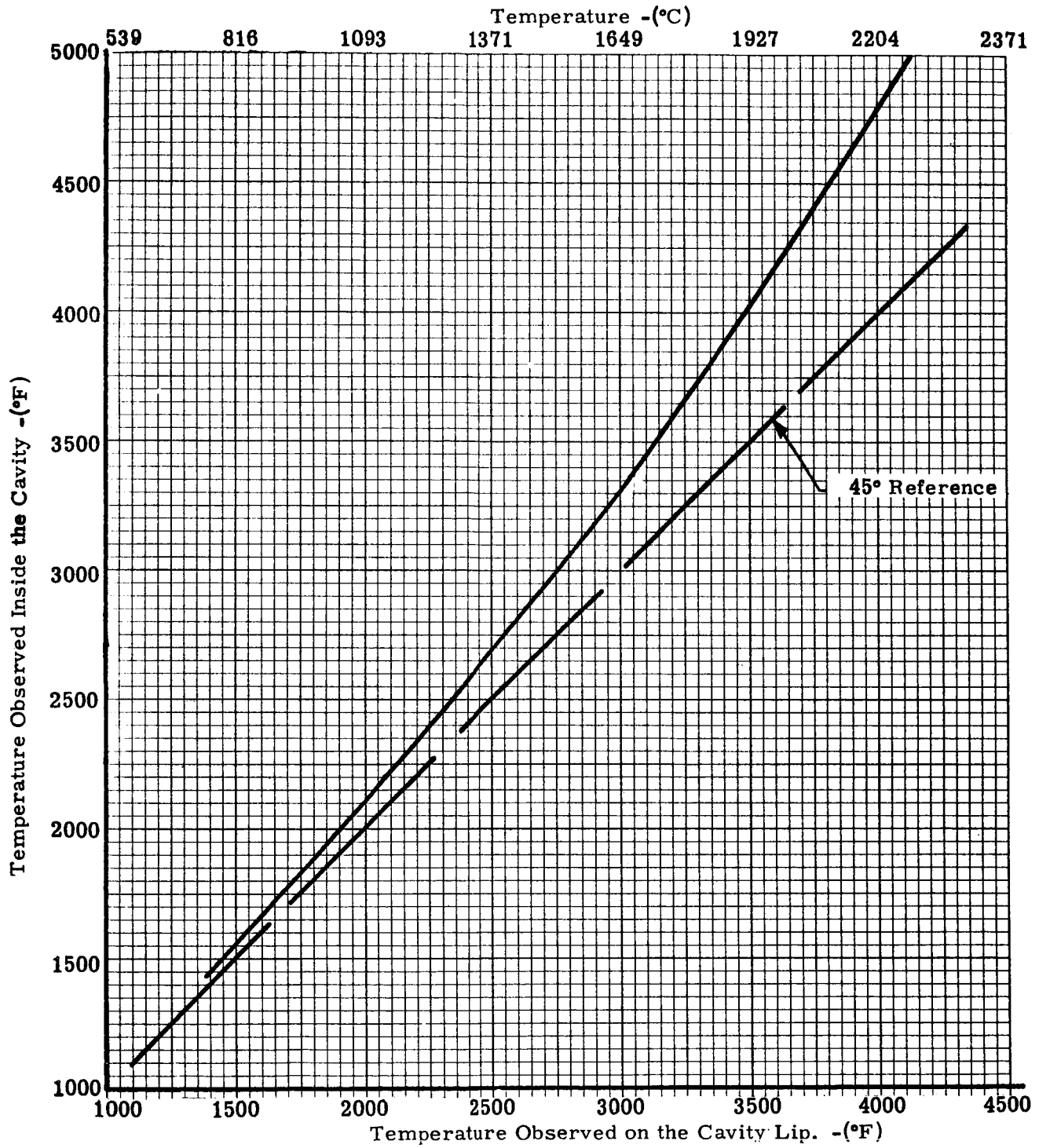


Figure 2. Calibration Curve for the $1\frac{3}{4}$ in. Deep Tungsten Blackbody Cavity Using an Optical Pyrometer

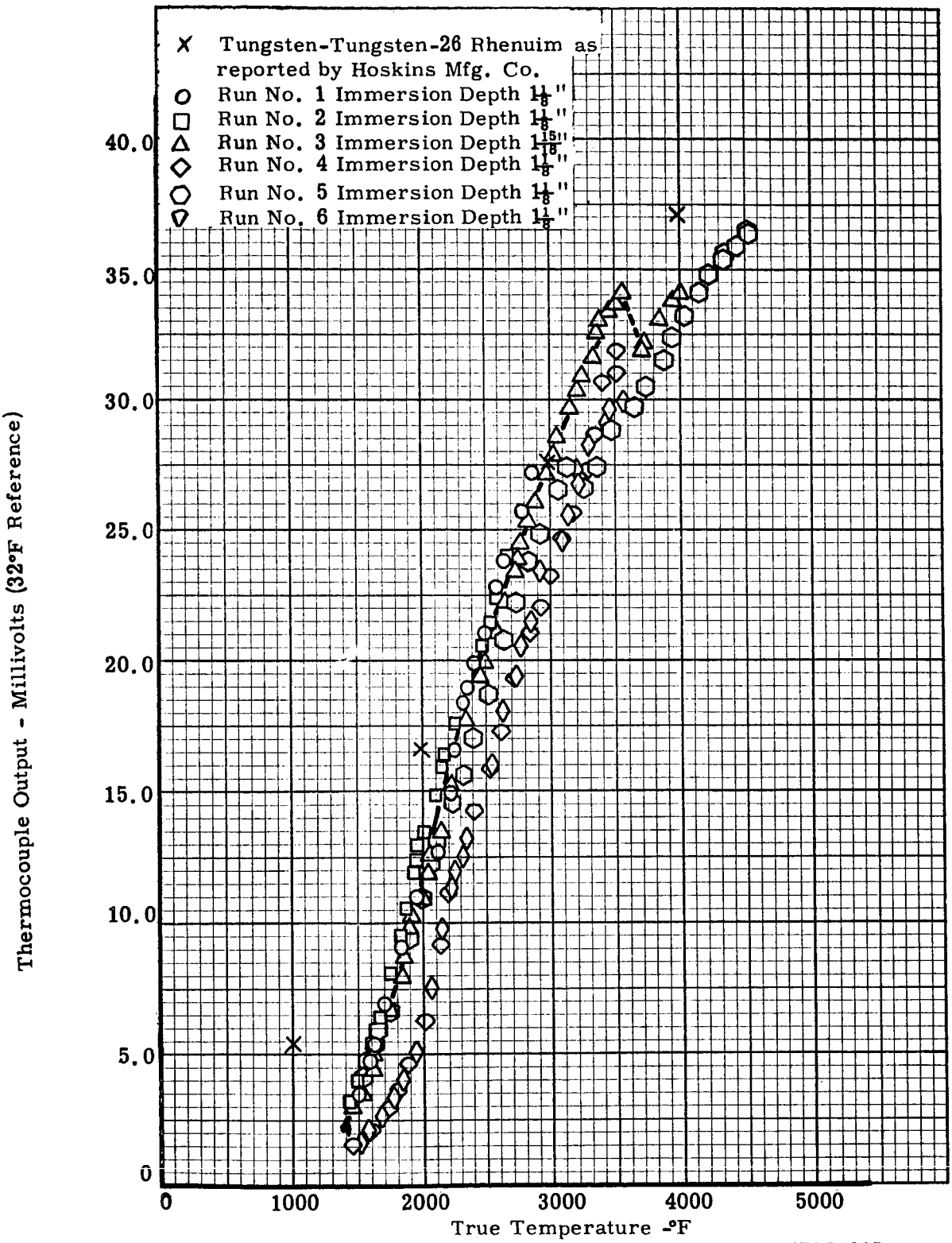


Figure 3. Calibration of ACL Thermocouple Assembly 4735-007 in Tungsten Blackbody Cavity Heated Inductively in Argon.

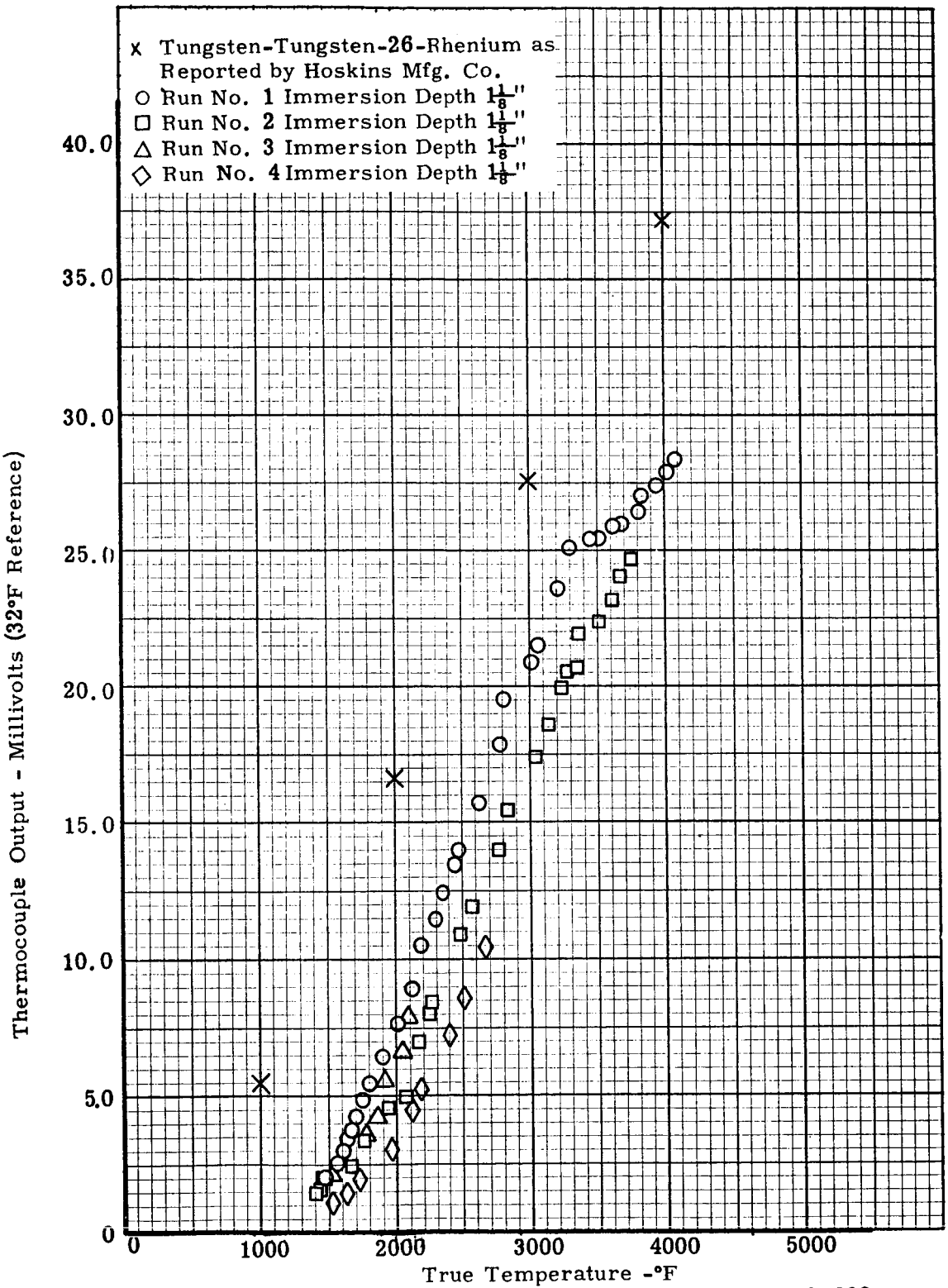


Figure 4. Calibration of ACL Thermocouple Assembly 4735-009 in Tungsten Blackbody Cavity Heated Inductively in Argon

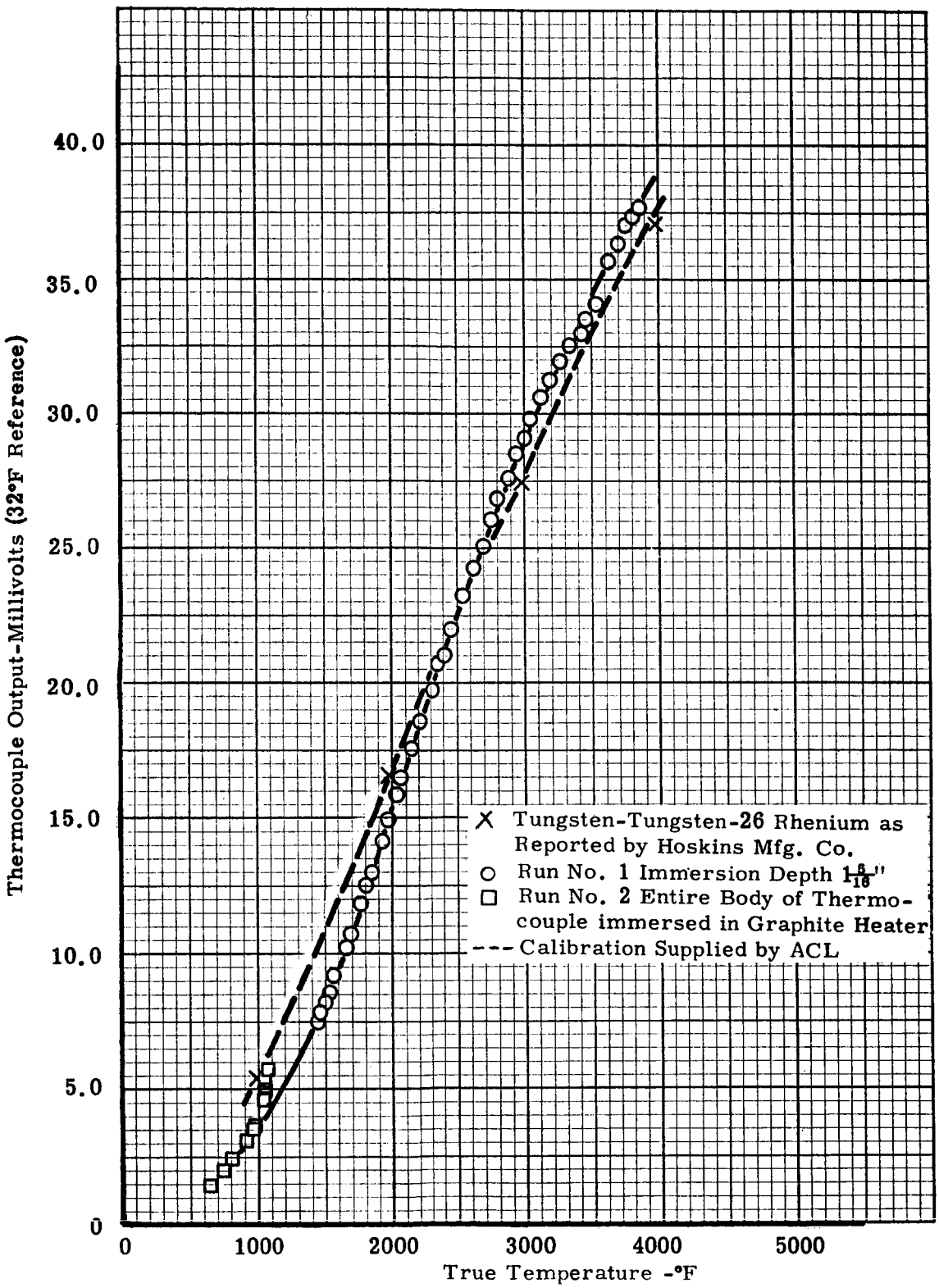


Figure 5. Calibration of ACL Thermocouple Assembly 4735-011 in Tungsten Blackbody Cavity Heated Inductively in Argon

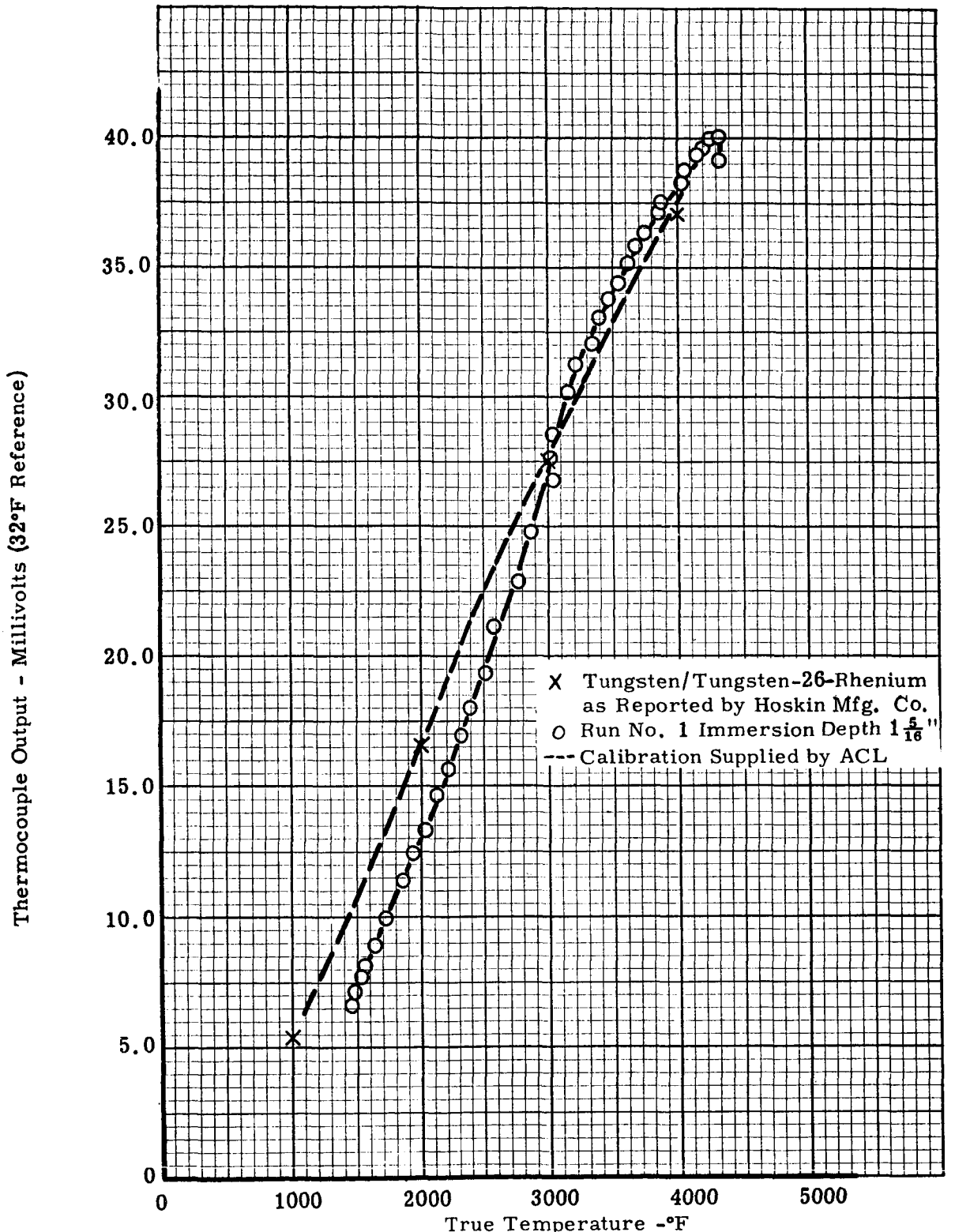


Figure 6. Calibration of ACL Thermocouple Assembly 4735-012Z in Tungsten Blackbody Cavity Inductively Heated in Argon.

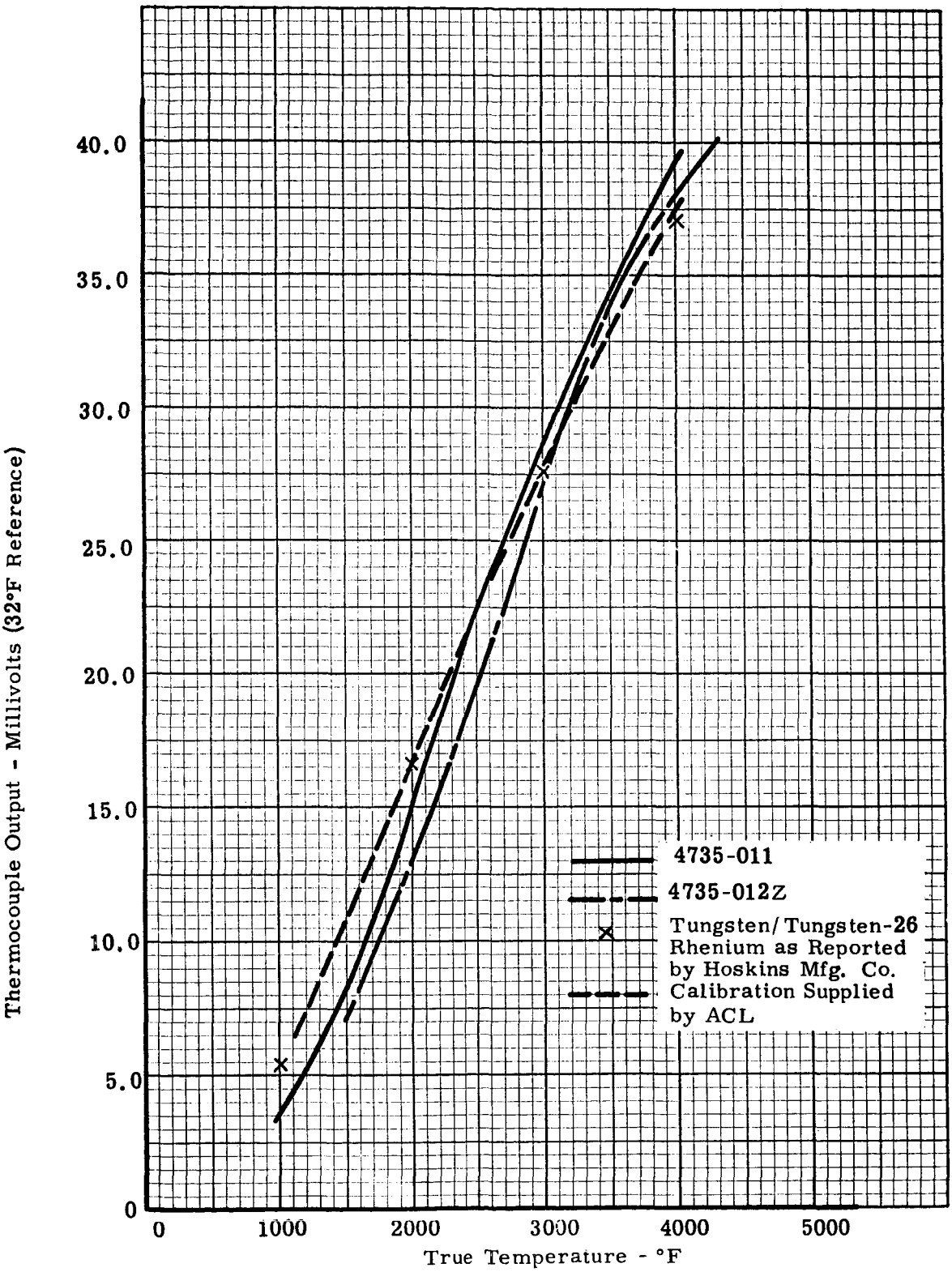


Figure 7. Comparison of Calibrations Obtained on ACL Thermocouples 4735-011 and 4735-012Z (first exposures)

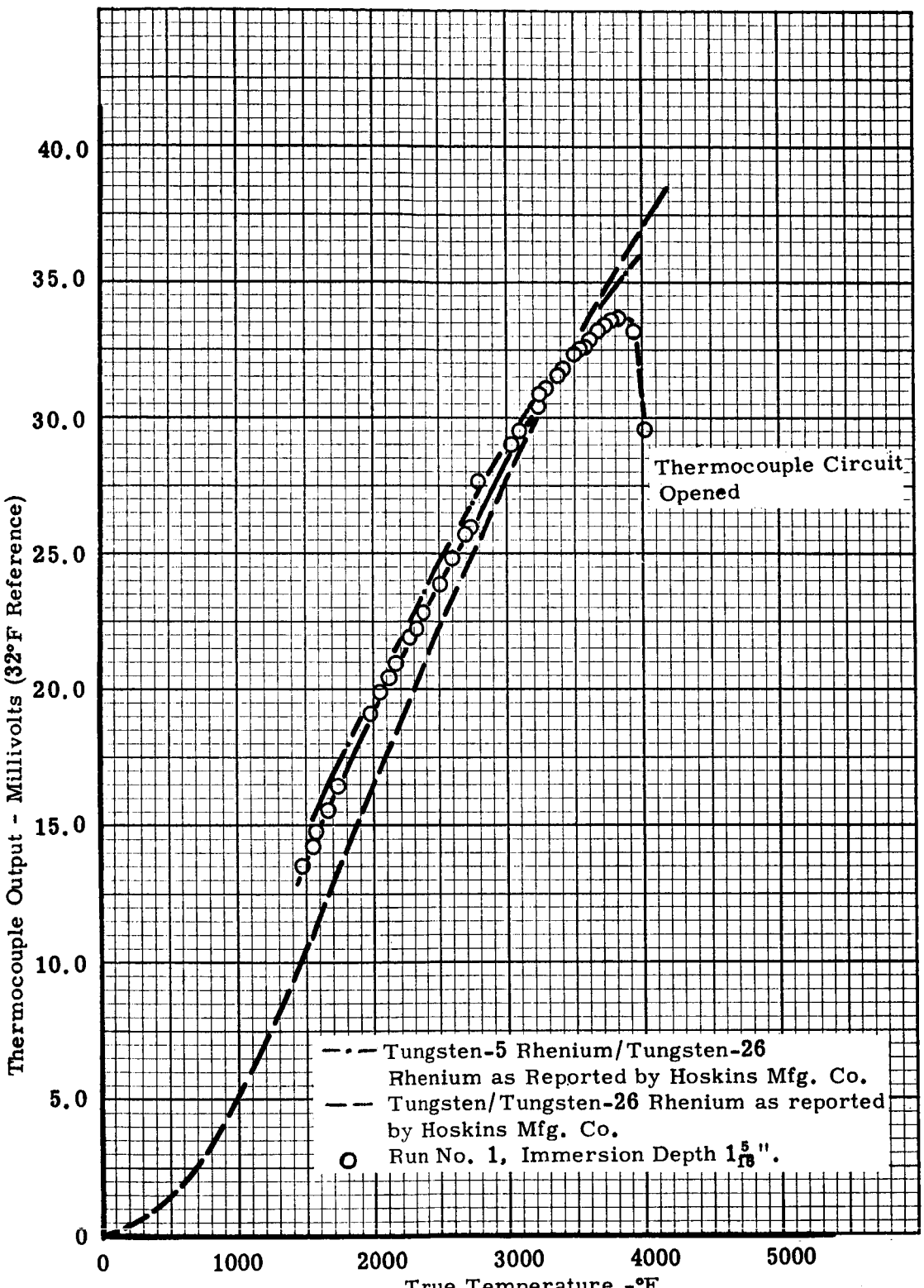


Figure 8. Calibration of Space Sciences Thermocouple Assembly 141-10253 in Tungsten Blackbody Cavity Inductively Heated in Argon.

After Exposure

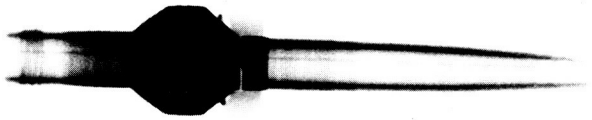
Figure 9. X-Ray of ACL Thermocouple No. 4735-003, After Exposure

X-Ray of ACL Thermocouple Assembly No. 4735-007 Showing the Eccentric Central Wire

X-Ray of ACL Thermocouple Assembly No. 4735-009 Showing the Central Wire in Contact with the Sheath and Other Material

Figure 10. X-Rays of ACL Thermocouple Assemblies 4735-007 and 4735-009

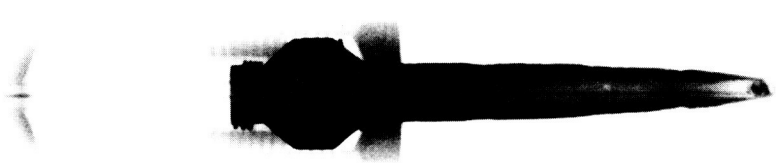
Before Exposure



After Exposure

Figure 11. X-Rays of ACL Thermocouple No. 4735-011, Before and After Exposure

Before Exposure



After Exposure

Figure 12. X-Rays of ACL Thermocouple No. 4735-012Z, Before and After Exposure

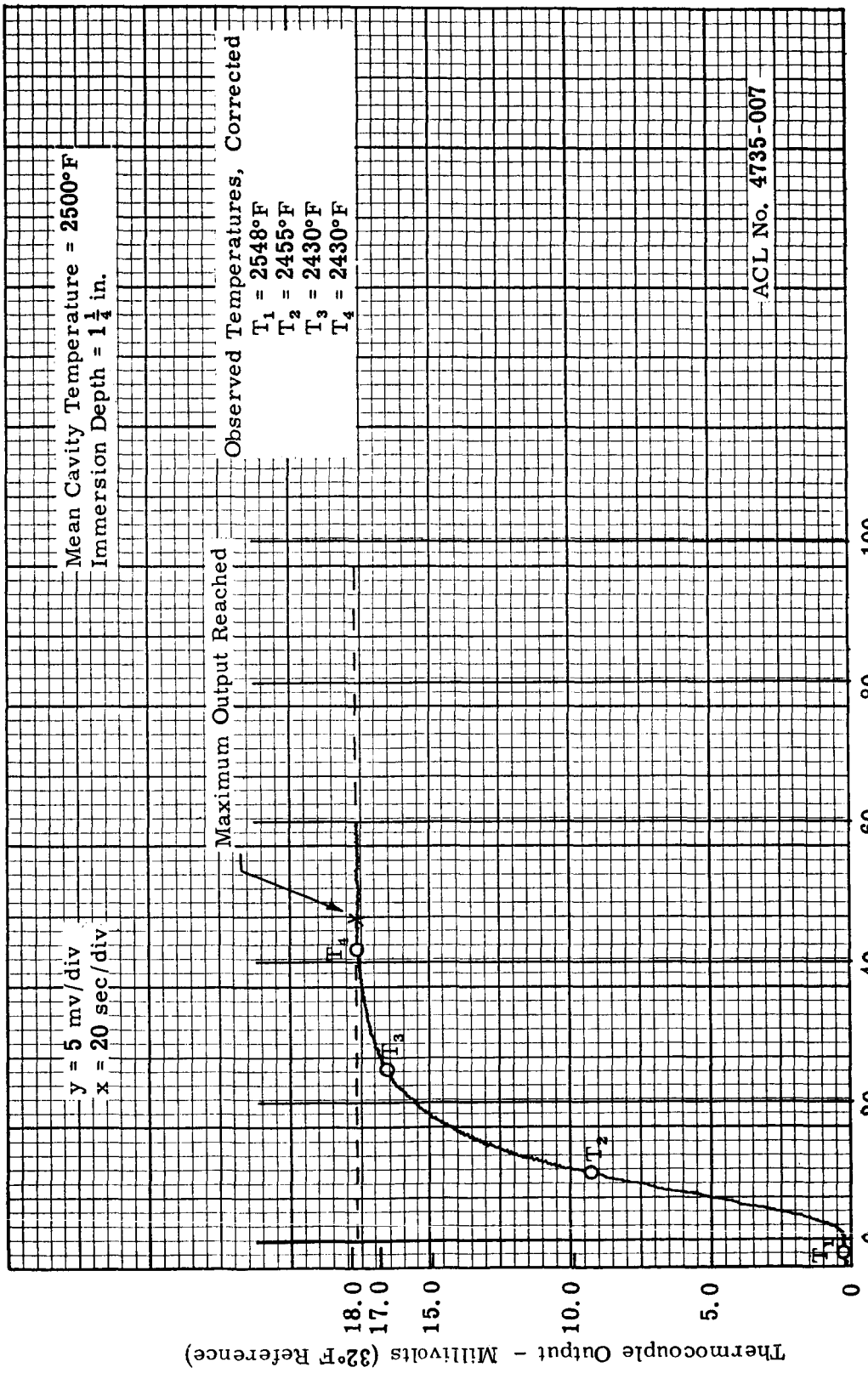


Figure 13. Typical Plot of the Time-Temperature Dependency of a High Temperature Thermocouple Assembly for a Mean Cavity Temperature of 2500°F (1371°C) and an Immersion Depth of 1 1/4 in. (Assembly 4735-007)

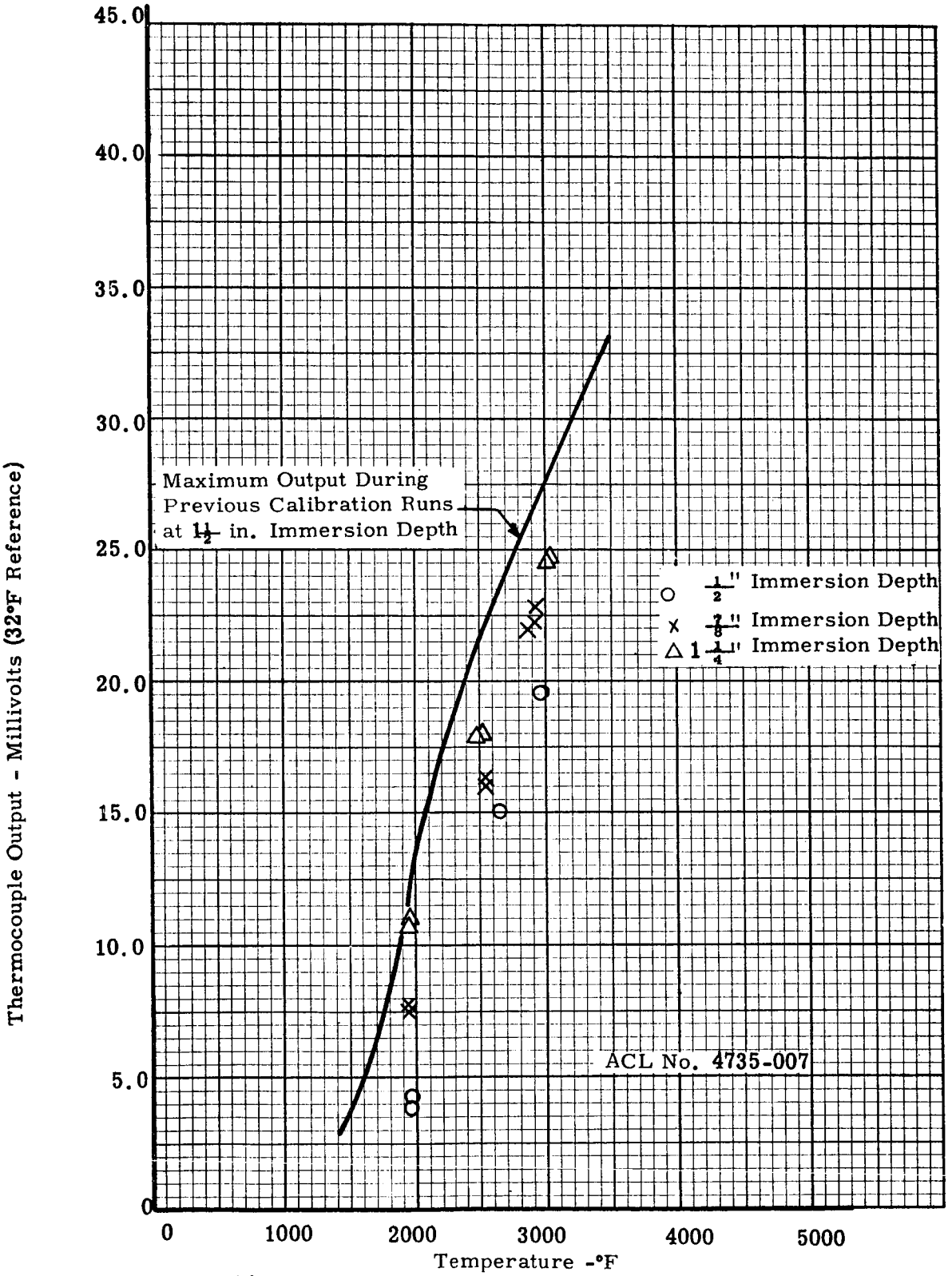


Figure 14. Thermocouple Output at Equilibrium Temperature for Three Immersion Depths Compared to the Maximum Output Obtained During Previous Runs for 1⅛ in. Immersion Depth

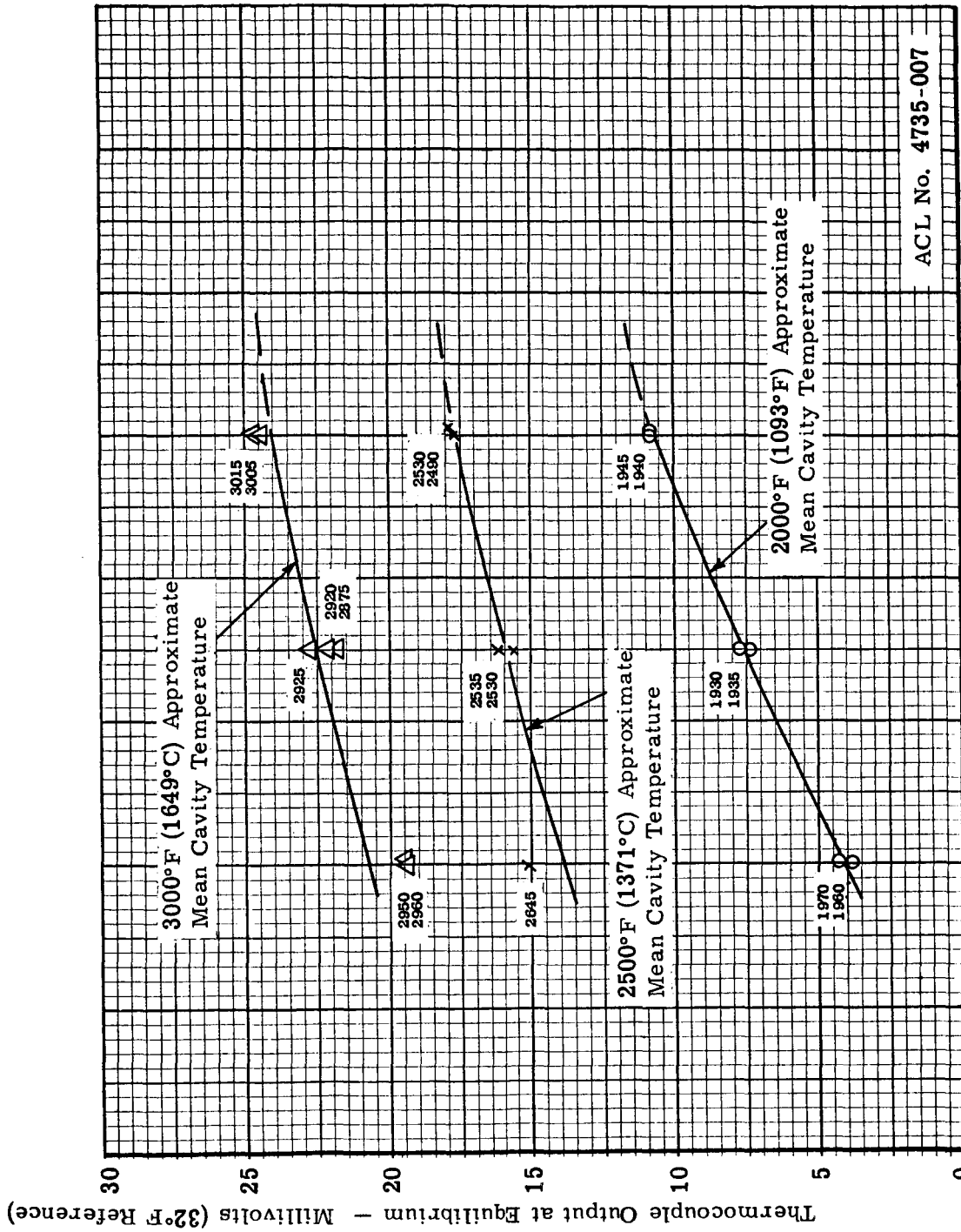


Figure 15. Effect of Immersion Depth on the Equilibrium Output from the Thermocouple Assembly

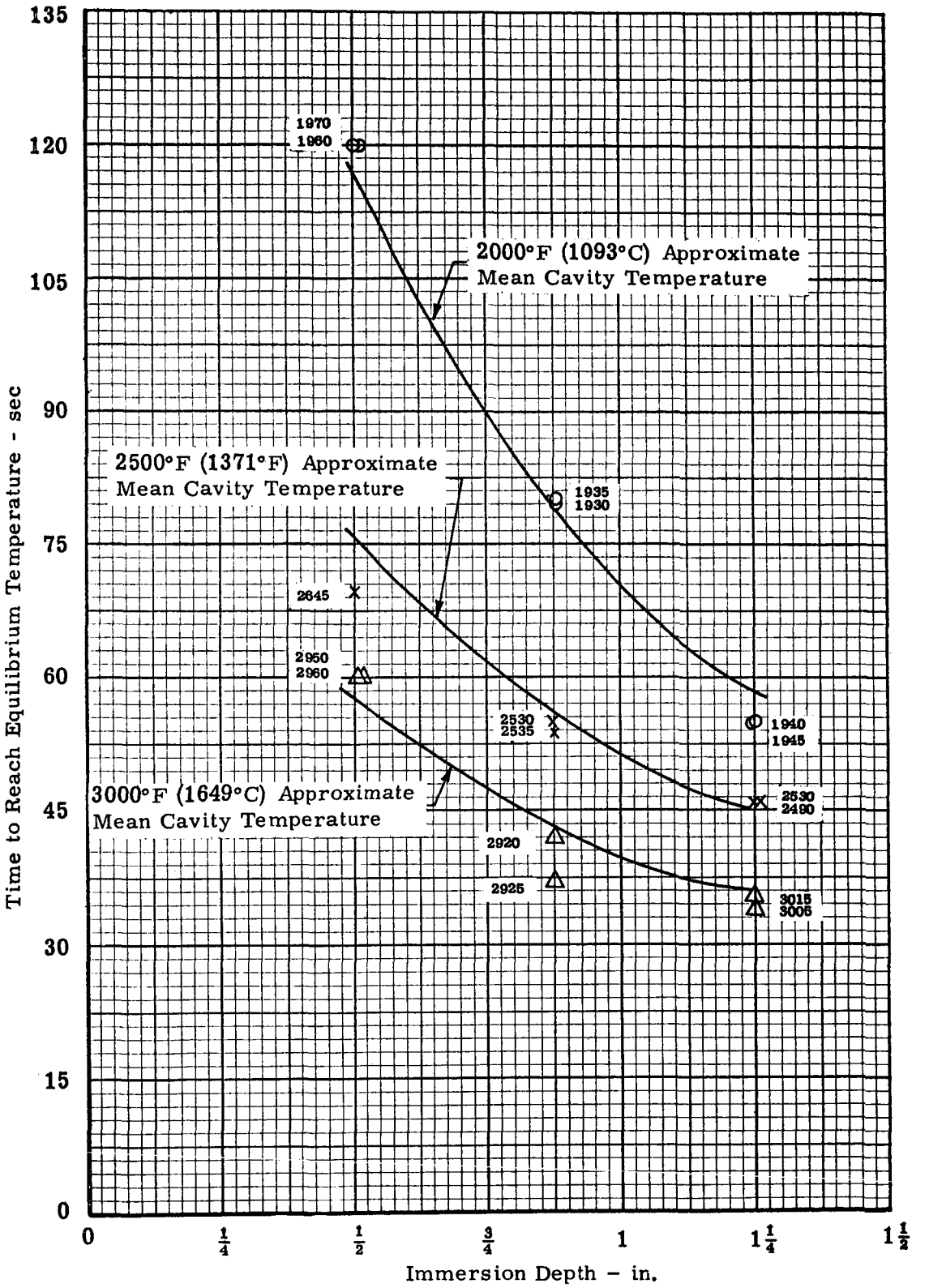


Figure 16. Effect of Immersion Depth on Time Required to Reach Maximum Output

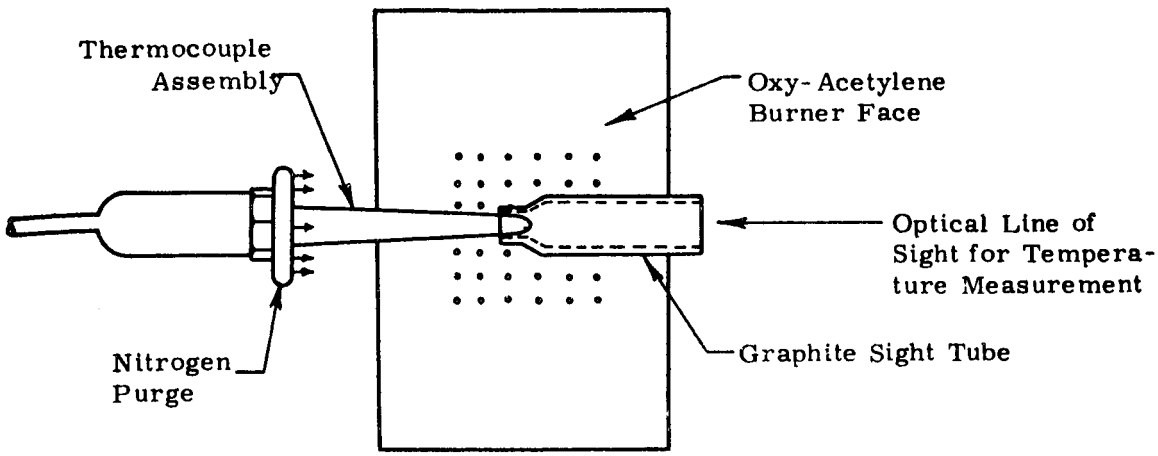


Figure 17. Schematic of Apparatus for Evaluations in the Oxy-Acetylene Burner

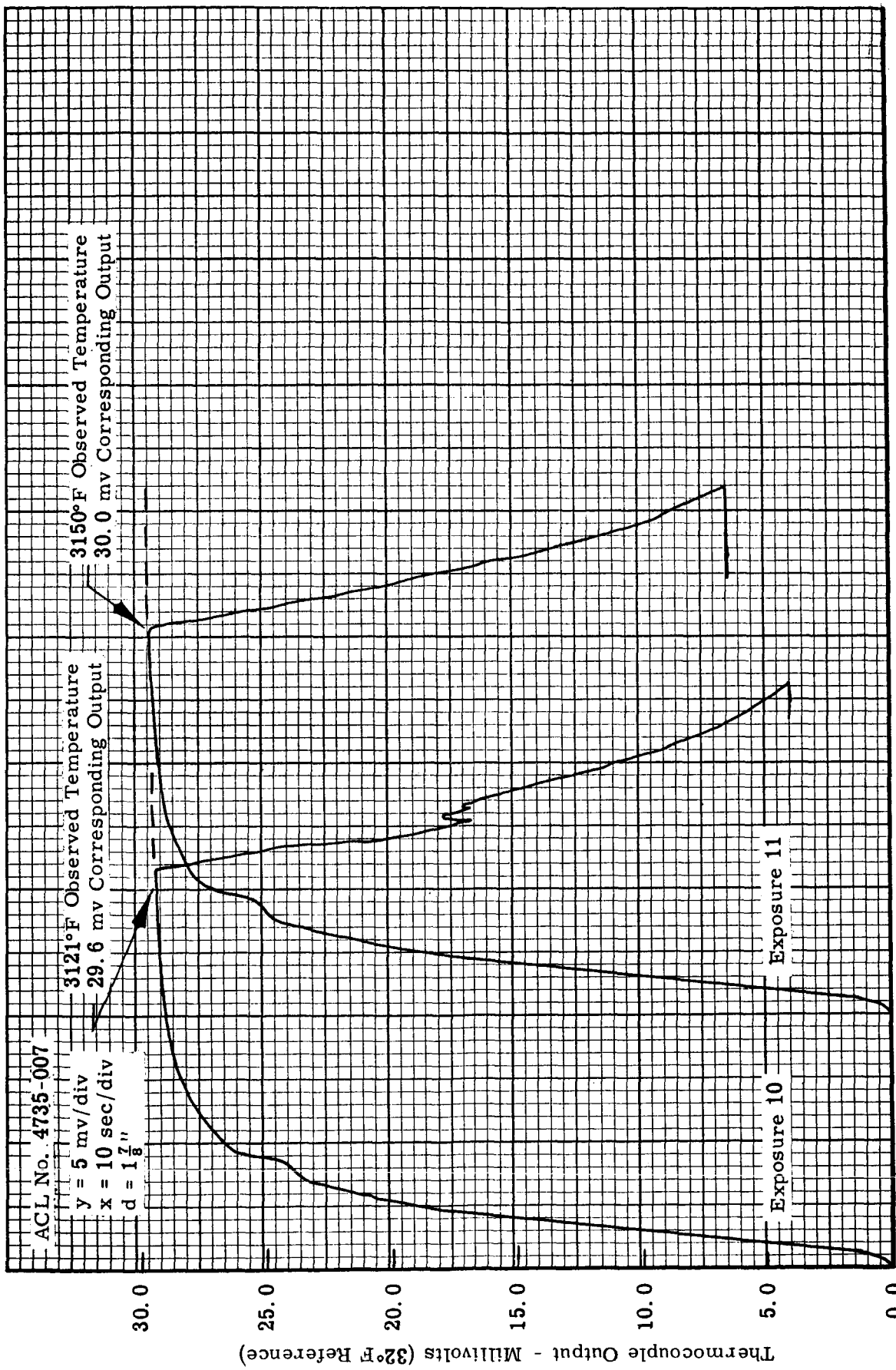


Figure 18. Thermoelectric Output from Assembly 4735-007 when Exposed to the Oxy-Acetylene Burner from a Distance of $1\frac{7}{8}$ in.

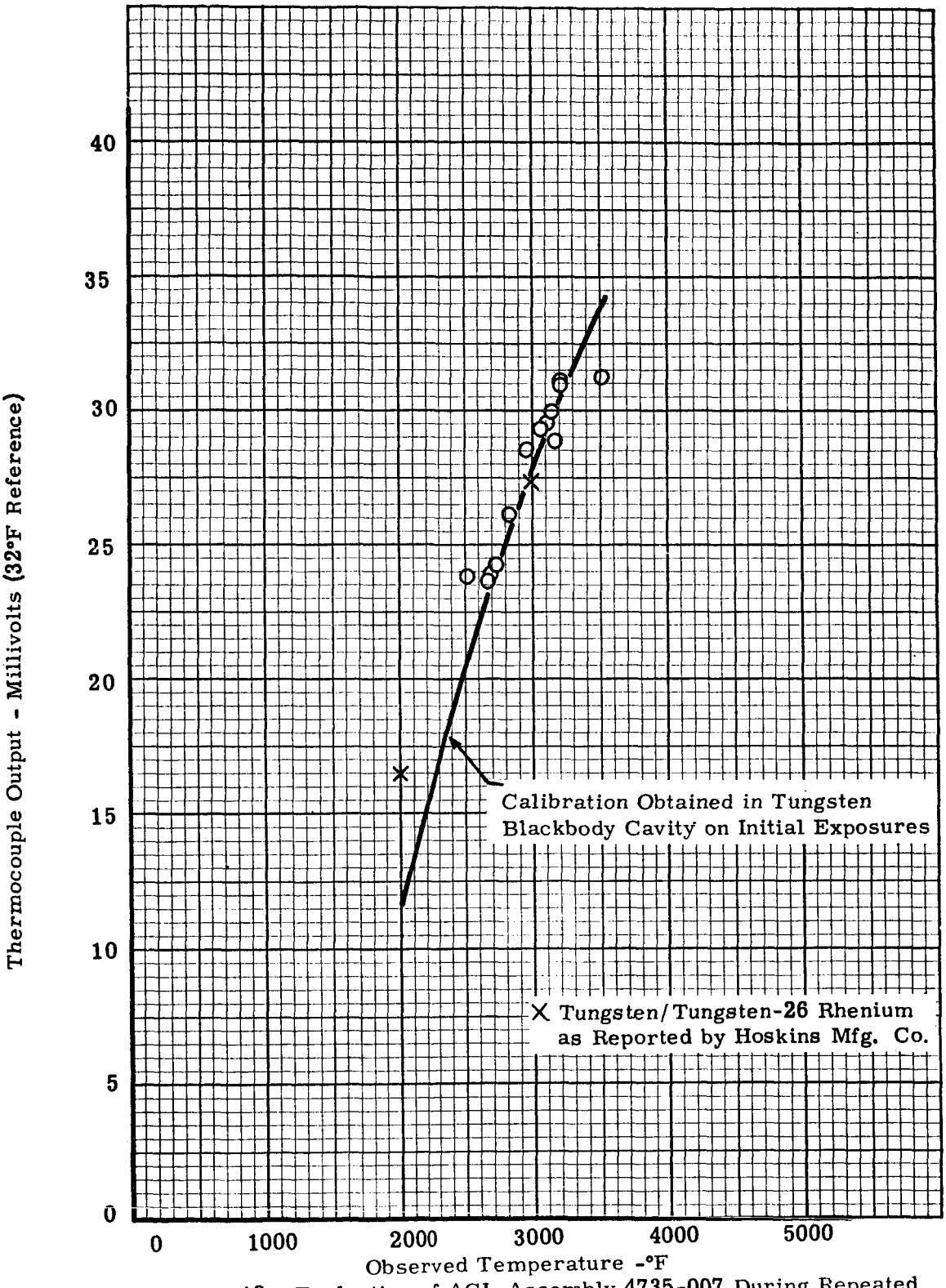


Figure 19. Evaluation of ACL Assembly 4735-007 During Repeated Exposures in Oxy-Acetylene Burner.

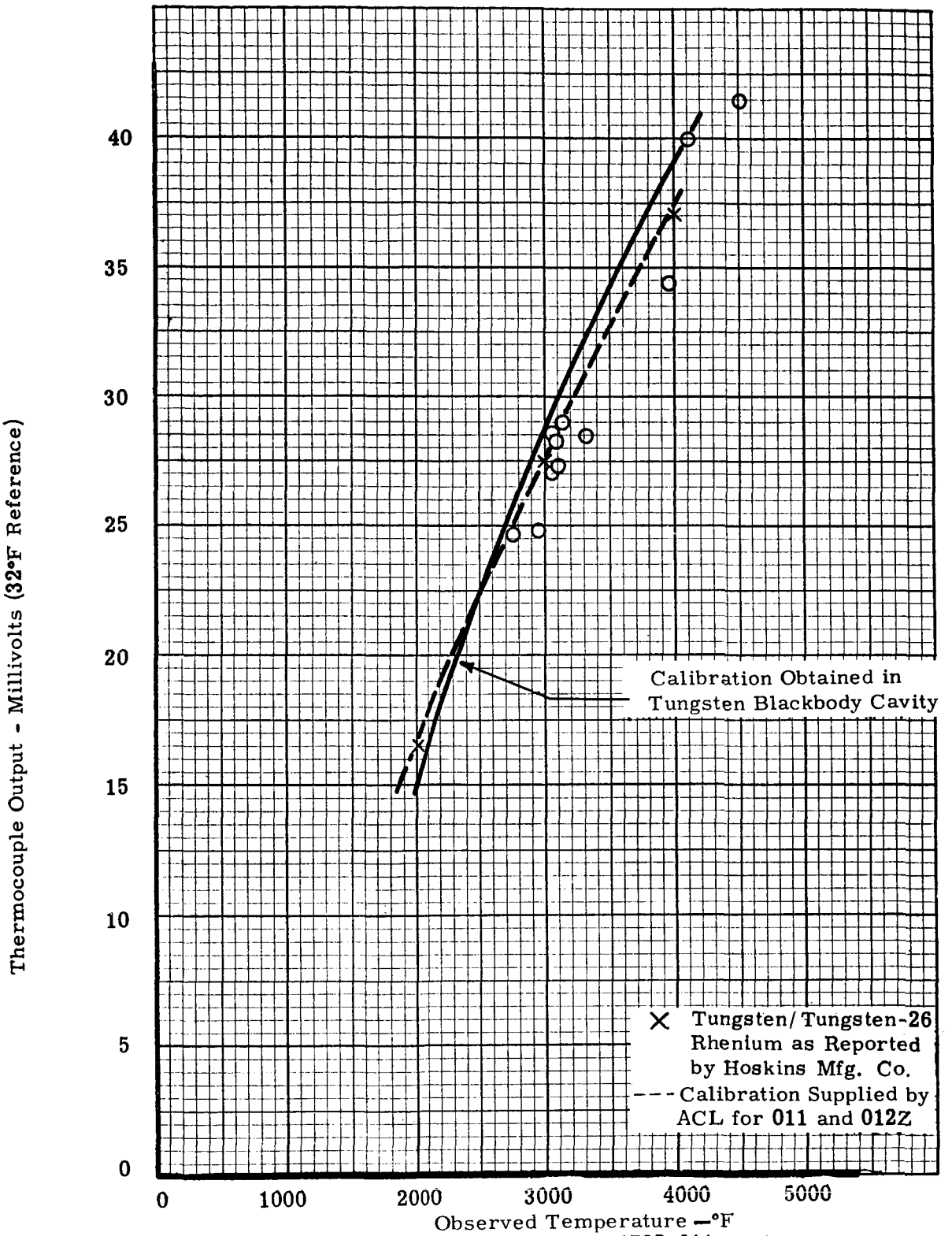


Figure 20. Evaluation of ACL Assembly 4735-011 During Repeated Exposures in Oxy-Acetylene Burner

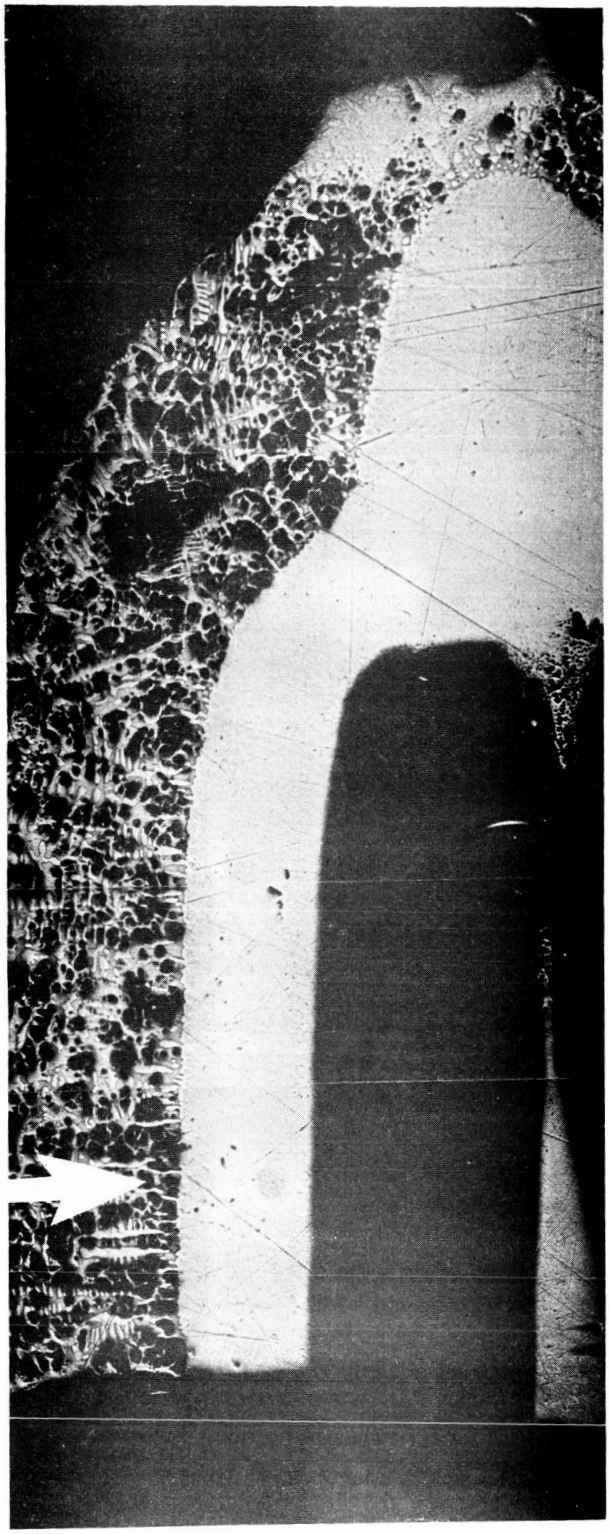


Figure 21. Photomicrograph of the Tip of ACL Thermocouple Assembly No. 4735-007 with Nital Etch, 50X Magnification

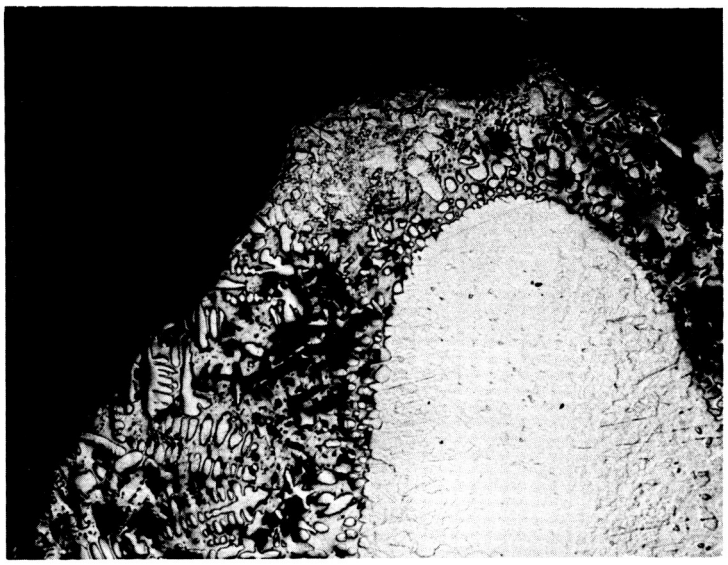


Figure 22. Photomicrograph of the Tip of ACL Thermocouple Assembly No. 4735-007 with a "Tungsten" Etch, 50X Magnification

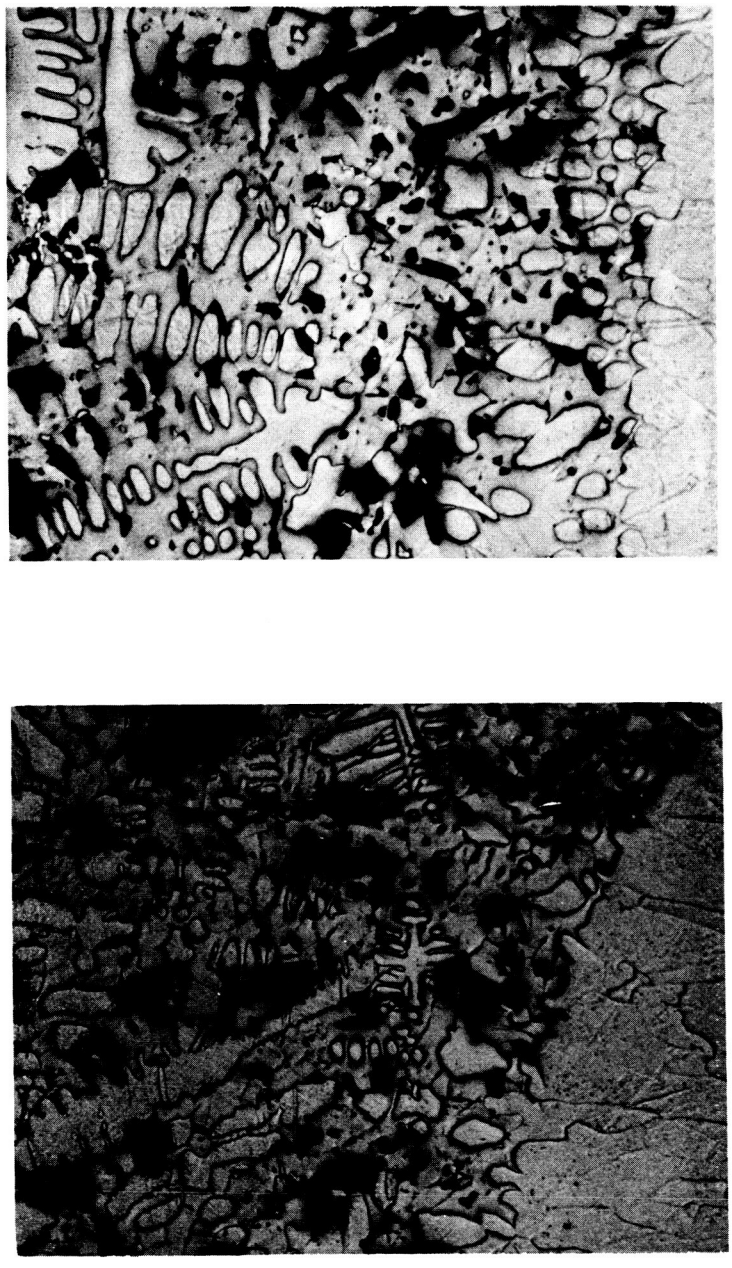
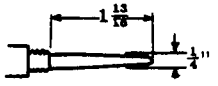
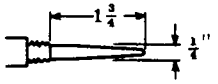
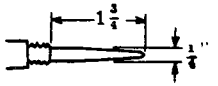
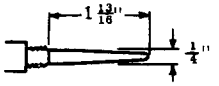
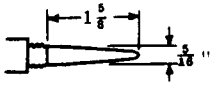
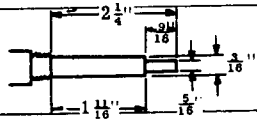
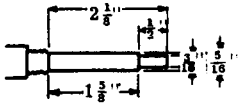


Figure 23. Photomicrographs of the Material around the Tungsten Sheath of ACL Thermocouple Assembly No. 4735-007 with a "Tungsten" Etch, 150X Magnification

Table 1. General Information Concerning Thermocouples Evaluated.

SRI No.	Manufacturer	Type or Model	Serial No.	Configuration (Approximate Dimensions)	Tests	Remarks
1	Auto-Control Laboratories	"1st Generation"	4735-003		1. Attempted calibration $1\frac{3}{8}$" deep Tungsten Cavity not successful. 2. X-rayed 2 views after exposure.	Output abnormally low and circuit opened at 1920°F.
2	Auto-Control Laboratories	"2nd Generation"	4735-007		1. Calibrated in tungsten cavity 6 times. First 3 runs in excellent agreement. 2. Evaluated for response time and immersion depth effects. 3. X-rayed after exposure. 4. Evaluated to 3525°F in oxy-acetylene burner.	Molten material from probe dripped into cavity during first run. A reaction occurred during the third exposure which cause lowering of the MV output. Graphite tube was welded to probe during burner exposure. Tip of probe was broken off during the attempt to remove graphite tube.
3	Auto-Control Laboratories	"2nd Generation"	4735-009		1. Calibrated 4 times in tungsten cavity with considerable variation in runs $1\frac{1}{8}$" immersion. 2. X-rayed.	When compared to 4735-007 in common hot zone, 4735-009 was found to have a lower output for the same exposure temperature.
4	Auto-Control Laboratories	"2nd Generation"	4735-011		1. X-rayed. 2. Calibrated to 4000°F in $1\frac{3}{4}$" deep tungsten cavity. 3. Entire housing immersed in graphite heater to check output at 1000°F in complete isothermal. 4. Calibrated to 4510°F in oxy-acetylene flame. 5. X-rayed.	Tungsten probe appeared streaked with irregular pits (after initial exposure). Good to 4500°F for 35 seconds in burner, then output fell off, tip broken during final x-ray.
5	Auto-Control Laboratories	"2nd Generation"	4735-012Z		1. X-rayed. 2. Calibrated in $1\frac{3}{4}$" deep tungsten cavity to 4300°F, $1\frac{5}{16}$" immersion. 3. X-rayed.	Output of thermocouple erratic. Zirconium oxide coating cracked and tungsten probe was pitted with irregular axial streaks.
6	[1]Space Sciences Incorporated	100-5-9	141-10249		1. Attempted calibration in tungsten cavity was not successful.	Circuit was open—possibly damaged during handling.
7	[1]Space Sciences Incorporated	100-5-9	141-10253		1. Calibrated in tungsten cavity to 4000°F with $1\frac{5}{16}$" immersion.	Output became erratic at 3950°F and the circuit opened.

Notes

1. No calibration supplied.

Table 2

Calibration of ACL Thermocouple Assembly
No. 4735-003 in Tungsten Blackbody Cavity Inductively Heated in Argon

Time	Cavity Lip °F	Thermocouple Output mv	True Temperature °F	Remarks
On 2:02				
2:13	1755	0.19	1840	Output Low
2:14	1930	0.26	2030	
2:16	2076	0.41	2200	
2:26	1810	2.23	1890	
2:32	1819	0.00	1920	Circuit Opened

Table 3

Calibration of ACL Thermocouple Assembly No. 4735-007
in Tungsten Blackbody Cavity Inductively Heated in Argon

Time	Temperature			Remarks
	Cavity Lip (°F)	Thermocouple Output (mv)	True (°F)	
Run No. 1				Teflon Guide, Asbestos paper
On 2:24				purge on 1:17
				Immersion depth = $1\frac{1}{8}$ inch.
2:38	1515	3.49	1515	
2:39	1607	4.73	1607	
2:40	1634	5.25	1634	
2:42	1722	6.94	1722	
2:44	1846	9.07	1850	
2:45	1959	10.95	1962	
2:46	2104	12.65	2135	
2:47	2179	14.90	2225	
2:48	2208	16.55	2255	
2:49	2271	18.29	2335	
2:50	2315	18.91	2375	
2:51	2348	19.91	2425	
2:52	2409	21.04	2500	
2:53	2498	22.76	2600	
2:54	2538	23.78	2650	
2:55	2653	25.73	2800	
2:56	2718	27.22	2880	
Off 2:57				Something appeared to be melting and dropping into the cavity.
Run No. 2				Teflon Guide, Asbestos paper, copper disc in cover plate.
On 8:29				1 1/8" immersion. Purge on
8:43	1438	3.17	1438	7:37.
8:44	1501	3.93	1501	
8:45	1689	6.41	1689	
8:46	1760	8.05	1760	
8:47	1832	9.50	1835	
8:47	1888	10.64	1895	

Table 3 (continued)

Calibration of ACL Thermocouple Assembly No. 4735-007
in Tungsten Blackbody Cavity Inductively Heated in Argon

	Temperature			
Time	Cavity Lip (°F)	Thermocouple Output (mv)	True (°F)	Remarks
8:48	1920	11.76	1930	
8:48	1958	12.37	1965	
8:49	1976	12.90	1987	
8:50	1999	13.39	2013	
8:51	2079	14.83	2110	
8:52	2121	15.85	2155	
8:52	2139	16.34	2175	
8:53	2219	17.59	2265	
8:54	2403	20.62	2495	
8:55	2440	21.44	2540	
8:56	2487	22.54	2590	
8:57	2536	23.33	2655	
8:57	2566	23.85	2685	
8:59				Power off Cavity repositioned
Run No. 3 On 10:14				Purge on 9:15 Immersion depth = $\frac{15''}{16}$ Teflon Guide, Asbestos paper and copper disc
10:28	1459	2.96	1459	
10:29	1542	3.53	1542	
10:29	1621	4.36	1621	
10:30	1670	4.97	1670	
10:32	1765	6.68	1765	
10:32	1764	6.95	1764	
10:33	1843	7.85	1845	
10:34	1880	8.68	1885	
10:35	1909	9.84	1915	
10:36	1923	10.15	1930	
10:37	1987	10.85	2000	
10:37	2029	11.83	2050	
10:38	2061	12.55	2080	

Table 3 (continued)

Calibration of ACL Thermocouple Assembly No. 4735-007
in Tungsten Blackbody Cavity Inductively Heated in Argon

	Temperature			
Time	Cavity Lip (°F)	Thermocouple Output (mv)	True (°F)	Remarks
10:38	2126	13.40	2155	
10:39	2189	15.10	2235	
10:39	2240	16.57	2295	
10:40	2309	17.73	2370	
10:41	2390	19.25	2480	
10:41	2418	19.88	2510	
10:42	2494	21.08	2600	
10:43	2541	22.23	2660	
10:43	2594	23.26	2730	
10:44	2621	23.90	2765	
10:44	2650	24.48	2795	
10:45	2682	25.34	2835	
10:47	2738	26.12	2900	
10:48	2792	27.09	2975	
10:48	2810	27.55	2995	
10:49	2839	27.84	3035	
10:50	2872	28.58	3080	
10:50	2950	29.70	3175	
10:51	2976	30.32	3215	
10:52	3013	30.91	3265	
10:52	3072	31.62	3335	
10:53	3110	32.51	3380	
10:53	3121	32.95	3400	
10:54	3177	33.36	3480	
10:54	3210	33.59	3515	
10:55	3261	34.05	3580	
10:56	3365	31.79	3715	Thermocouple output dropped
10:56	3378	32.08	3735	
10:57	3462	33.08	3850	
10:57	3539	33.71	3960	
10:58	3579	34.12	4015	Observed smoke
Off 10:59				Post - run inspection revealed that the point of the probe appeared to have melted.

Table 3 (continued)

Calibration of ACL Thermocouple Assembly No. 4735-007
in Tungsten Blackbody Cavity Inductively Heated in Argon

Time	Temperature			Remarks
	Cavity Lip	Thermocouple Output (mv)	True (°F)	
Run No. 4				Immersion Depth = $1\frac{1}{8}$ inch. Teflon Guide, Asbestos paper and copper disc in cover plate. Purge on 7:30
On 8:45				
9:03	1521	1.57	1521	
9:06	1599	2.13	1599	
9:07	1692	2.62	1692	
9:08	1779	3.27	1779	
9:09	1862	4.01	1865	
9:10	1949	5.03	1955	
9:11	2055	7.48	2075	
9:12	2123	9.80	2160	
9:13	2188	11.30	2230	
9:13	2222	11.90	2270	
9:14	2275	12.52	2335	
9:15	2308	13.23	2365	
9:16	2465	16.04	2565	
9:17	2528	17.97	2645	
9:18	2609	19.38	2745	
9:18	2638	20.48	2785	
9:19	2702	21.40	2860	
9:20	2801	23.44	2935	
9:21	2890	24.45	3105	
9:21	2922	25.57	3145	
9:21	2981	26.65	3220	
9:22	2974	27.32	3215	
9:22	3050	28.21	3305	
9:23	3150	29.05	3440	
9:23	3183	29.55	3480	
9:24	3192	29.86	3495	
Off 9:25				

Table 3 (continued)

Calibration of ACL Thermocouple Assembly No. 4735-007
in Tungsten Blackbody Cavity Inductively Heated in Argon

Time	Temperature: Cavity Lip (°F)	Temperature: Thermocouple Output (mv)	Temperature: True (°F)	Remarks
Run No. 5				Teflon Guide, Asbestos paper, Zirconia ring insulation Immersion depth = 1⅛ inch. Purge on 7:30
On 8:10				
8:36	1443	2.85	1443	
8:37	1501	3.52	1501	
8:38	1541	4.07	1541	
8:40	1599	4.72	1599	
8:41	1645	5.30	1645	
8:42	1679	5.88	1679	
8:43	1758	6.67	1758	
8:45	1834	8.16	1840	
8:48	1917	9.43	1925	
8:50	1990	11.00	2005	
8:52	2049	12.40	2070	
8:54	2089	13.10	2120	
8:55	2190	14.49	2235	
8:56	2275	15.74	2340	
8:57	2343	17.03	2415	
8:58	2439	18.65	2535	
8:59	2540	20.78	2655	
9:00	2615	22.24	2755	
9:01	2690	23.71	2850	
9:02	2763	24.77	2935	
9:03	2870	26.47	3075	
9:04	2921	27.35	3145	
9:07	3020	26.55	3270	
9:09	3120	27.43	3375	
9:10	3190	28.76	3495	
9:11	3297	29.22	3670	
9:12	3380	30.45	3750	
9:13	3490	31.48	3895	
9:14	3540	32.32	3960	

Table 3 (continued)

Calibration of ACL Thermocouple Assembly No. 4735-007
in Tungsten Blackbody Cavity Inductively Heated in Argon

Time	Temperature			Remarks
	Cavity Lip (°F)	Thermocouple Output (mv)	True (°F)	
9:14	3607	33.19	4050	
9:15	3690	34.06	4165	
9:16	3740	34.79	4235	
9:17	3822	35.39	4350	
9:18	3841	35.60	4370	
9:19	3907	35.92	4460	
9:20	3960	36.38	4535	
9:20	3950	36.50	4520	Water temperature = 180°F
Off 9:21				
Run No. 6				Immersion depth = $1\frac{1}{8}$ inch. Threaded into copper fitting in water-cooled cover plate, purge on 11:20
On 1:24				
1:50	1467	1.48	1467	
1:51	1606	2.13	1606	
1:52	1739	2.95	1739	
1:53	1813	3.61	1813	
1:54	1896	4.63	1900	
1:55	2008	6.20	2025	
1:56	2105	9.09	2140	
1:57	2171	11.13	2215	
1:58	2348	14.15	2425	
1:59	2446	15.77	2545	
2:00	2520	17.24	2635	
2:01	2600	19.17	2735	
2:02	2699	20.95	2855	
2:02	2759	21.99	2930	
2:03	2819	23.23	3010	
2:04	2891	24.66	3100	
2:05	2959	25.58	3190	
2:06	3060	27.32	3315	
2:07	3110	28.72	3380	
2:08	3178	30.68	3425	Thermoelectric output very erratic
2:09	3231	31.80	3540	
2:10	3221	31.00	3530	
2:11	3343	32.75	3685	
2:12	3542	–	–	Could not read thermocouple output; too erratic
Off 2:13				

Table 4

Calibration of ACL Thermocouple Assembly No. 4735-009
in Tungsten Blackbody Cavity Inductively Heated in Argon

Time	Temperature: Cavity Lip (°F)	Temperature: Thermocouple Output (mv)	Temperature: True (°F)	Remarks
Run No. 1				Purge on 12:35. Teflon Guide, Asbestos paper, and copper disc in cover plate Immersion depth = 1 1/8 inch.
On 2:10				
2:39	1492	1.97	1492	
2:40	1574	2.54	1574	
2:41	1609	2.91	1609	
2:42	1644	3.43	1644	
2:43	1681	3.73	1681	
2:44	1709	4.15	1709	
2:45	1766	4.75	1766	
2:46	1810	5.38	1810	
2:47	1902	6.37	1910	
2:48	2012	7.64	2025	
2:50	2090	8.94	2120	
2:52	2151	10.50	2190	
2:53	2246	11.45	2300	
2:54	2306	12.36	2365	
2:55	2371	13.38	2450	
2:56	2400	13.95	2490	
2:58	2520	15.72	2635	
2:59	2647	17.82	2790	
2:59	2749	19.52	2915	
3:00	2820	20.75	3015	
3:01	2860	21.50	3065	
3:02	2982	23.58	3215	
3:02	3081	25.08	3300	
3:04	3159	25.39	3450	
3:04	3212	25.44	3515	
3:05	3295	25.82	3635	
3:06	3330	25.92	3680	
3:06	3435	26.54	3815	
3:07	3445	27.00	3835	
3:07	3535	27.38	3955	
3:08	3580	27.92	4010	
3:08	3640	28.26	4095	Maximum water temperature = 184°F
Off 3:09				

Table 4 (continued)

Calibration of ACL Thermocouple Assembly No. 4735-009
in Tungsten Blackbody Cavity Inductively Heated in Argon

	Temperature			
Time	Cavity Lip (°F)	Thermocouple Output (mv)	True (°F)	Remarks
Run No. 2				Purge on 11:32. Immersion depth = 1 1/8 inch. Teflon Guide, Asbestos paper, zirconia ring insulation
On 12:52				
1:15	1411	1.39	1411	
1:17	1445	1.56	1445	
1:18	1490	1.75	1490	
1:20	1690	2.39	1690	
1:23	1767	3.32	1767	
1:24	1939	4.57	1950	
1:26	2050	5.95	2075	
1:27	2134	7.00	2175	
1:28	2206	7.99	2255	
1:30	2232	8.41	2280	
1:32	2409	10.79	2500	
1:34	2474	11.78	2580	
1:36	2647	14.00	2790	
1:39	2684	15.36	2840	
1:40	2855	17.37	3055	
1:41	2921	18.55	3140	
1:42	2989	19.90	3230	
1:43	3039	20.60	3295	
1:44	3092	20.70	3355	
1:45	3181	21.90	3475	
1:46	3211	22.32	3515	
1:48	3290	23.20	3625	
1:49	3342	24.06	3690	
1:50	3392	24.74	3755	
Off 1:52				
Run No. 3				Same set-up as previous run
On 1:45				
2:11	1435	1.70	1435	
2:12	1451	1.93	1451	
2:13	1511	2.15	1511	

Table 4 (continued)

Calibration of ACL Thermocouple Assembly No. 4735-009
in Tungsten Blackbody Cavity Inductively Heated in Argon

	Temperature			
Time	Cavity Lip (°F)	Thermocouple Output (mv)	True (°F)	Remarks
2:16	1796	3.52	1796	
2:17	1870	4.17	1875	
2:19	1955	5.48	1965	
2:20	2033	6.63	2055	
2:23	2046	7.46	2070	
2:24	2069	7.79	2100	
Off 2:27				Output from thermocouple too low
Run No. 4				Purge on 8:35. Assembly threaded into copper fitting in water-cooled cover plate Immersion depth = 1 1/8 inch.
On 9:03				
9:29	1536	1.12	1536	
9:30	1642	1.47	1642	
9:32	1740	1.95	1740	
9:34	1964	3.14	1975	
9:36	2090	4.45	2120	
9:37	2149	5.17	2190	
9:39	2336	7.16	2410	
9:41	2416	8.57	2505	
9:42	2550	10.31	2670	
Off 9:43				Output unreasonably low

Table 5

Calibration of ACL Thermocouple Assembly No. 4735-011
in Tungsten Blackbody Cavity Inductively Heated in Argon

Time	Temperature: Cavity Lip (°F)	Temperature: Thermocouple Output (mv)	Temperature: True (°F)	Remarks
On 3:07				Immersion Depth 1 5/16 inch
3:30	1409	7.49	1455	
3:30	1425	7.76	1475	
3:31	1458	8.18	1505	
3:32	1490	8.57	1545	
3:32	1533	9.18	1585	
3:33	1608	10.20	1670	
3:33	1642	10.74	1710	
3:34	1695	11.81	1765	
3:35	1745	12.53	1825	
3:35	1778	13.04	1870	
3:36	1848	14.09	1935	
3:36	1894	14.93	1990	
3:37	1940	15.75	2045	
3:37	1983	16.51	2085	
3:38	2043	17.55	2158	
3:38	2099	18.64	2225	
3:39	2180	19.73	2320	
3:39	2231	20.67	2370	
3:40	2270	21.05	2425	
3:40	2319	21.97	2470	
3:41	2389	23.18	2555	
3:41	2457	24.23	2640	
3:42	2510	25.09	2705	
3:42	2570	26.10	2770	
3:43	2610	26.77	2815	
3:43	2672	27.59	2900	
3:44	2717	28.48	2945	
3:44	2760	29.13	3005	
3:45	2801	29.81	3060	
3:45	2861	30.63	3130	
3:46	2910	31.19	3200	
3:47	2970	31.96	3275	
3:47	3010	32.51	3345	
3:48	3081	33.04	3430	
3:48	3107	33.45	3465	

Table 5 (continued)

Calibration of ACL Thermocouple Assembly No. 4735-011
in Tungsten Blackbody Cavity Inductively Heated in Argon

	Temperature			
Time	Cavity Lip (°F)	Thermocouple Output (mv)	True (°F)	Remarks
3:49	3165	34.14	3540	
3:50	3225	35.72	3630	
3:51	3271	36.32	3705	
3:51	3317	36.96	3760	
3:52	3360	37.42	3820	
Off 3:52	3387	37.65	3870	

Table 6

Calibration of ACL Thermocouple Assembly No. 4735-011
with Entire Thermocouple Body Immersed in Graphite Heater

Time	Furnace Temperature °F	Thermocouple Output mv	Remarks
On 9:16			Furnace temperature monitored with chromel-alumel thermocouple wired to thermocouple body.
9:24	654	1.36	
9:31	764	1.95	
9:37	820	2.41	
9:43	926	3.09	
9:51	978	3.51	
9:55	991	3.62	
9:58	996	3.68	
10:02	1043	4.62	
10:04	1049	4.82	
10:07	1055	4.95	
10:11	1063	5.05	
10:22	1051	5.01	
10:34	1054	4.84	
10:37	1071	5.25	
10:42	1074	5.48	
10:45	1076	5.53	
Off 10:58	1086	5.68	

Table 7

Calibration of ACL Thermocouple Assembly No. 4735-012Z
in Tungsten Blackbody Cavity Inductively Heated in Argon

Time	Temperature			Remarks
	Cavity Lip (°F)	Thermocouple Output (mv)	True (°F)	
On 9:47				Immersion Depth = 1 5/16 inch
10:03	1408	6.72	1455	
10:04	1437	7.20	1485	
10:05	1473	7.69	1525	
10:06	1502	8.15	1555	
10:07	1579	9.02	1635	
10:08	1663	9.99	1720	
10:09	1768	11.43	1850	
10:09	1836	12.47	1935	
10:10	1909	13.37	2005	
10:10	2010	14.71	2115	
10:11	2083	15.74	2205	
10:12	2172	16.95	2315	
10:12	2250	18.12	2395	
10:13	2358	19.38	2515	
10:13	2426	21.15	2595	
10:14	2581	22.91	2782	
10:15	2660	24.90	2875	
10:15	2779	26.84	3035	
10:16	2758	27.73	3005	
10:17	2788	28.57	3045	
10:17	2881	30.15	3160	
10:18	2918	31.30	3210	
10:18	3013	32.05	3340	
10:19	3060	33.11	3400	
10:19	3119	33.83	3475	
10:20	3180	34.45	3555	
10:21	3218	35.18	3615	
10:21	3261	35.93	3685	
10:22	3310	36.39	3750	
10:23	3381	37.18	3860	
10:23	3402	37.63	3890	
10:24	3500	38.30	4035	
10:25	3527	38.83	4070	
10:25	3575	39.42	4150	
10:26	3620	39.65	4215	
10:27	3659	40.00	4275	
10:28	3680	40.10	4310	
Off 10:29	3690	39.20	4325	TC output became erratic, run ended.

Table 8

Calibration of Space Sciences Thermocouple No. 141-10253
in Tungsten Blackbody Cavity Inductively Heated in Argon

Time	Temperature: Cavity Lip (°F)	Temperature: Thermocouple Output (mv)	Temperature: True (°F)	Remarks
On 3:16				Immersion Depth = 1 5/16"
3:33	1430	13.49	1480	
3:34	1482	14.23	1540	
3:35	1531	14.80	1585	
3:38	1610	15.60	1670	
3:39	1669	16.35	1735	
3:42	1900	19.10	1995	
3:46	1960	19.85	2060	
3:48	2008	20.36	2120	
3:49	2062	20.90	2175	
3:50	2140	21.91	2275	
3:51	2180	22.19	2320	
3:53	2239	22.76	2385	
3:54	2349	23.94	2505	
3:55	2429	24.84	2605	
3:56	2510	25.66	2700	
3:58	2540	26.00	2735	
3:59	2676	27.70	2900	
4:01	2785	29.03	3040	
4:02	2835	29.50	3100	
4:04	2866	29.69	3145	
4:05	2930	30.35	3230	
4:05	2945	30.75	3245	
4:06	2990	31.10	3300	
4:07	3048	31.50	3380	
4:08	3076	31.78	3425	
4:09	3132	32.25	3500	
4:10	3162	32.46	3540	
4:11	3185	32.62	3580	
4:12	3219	32.90	3620	
4:13	3262	33.16	3680	
4:15	3298	33.43	3730	
4:16	3332	33.62	3780	
4:17	3367	33.68	3830	
4:18	3442	33.21	3945	
Off 4:19	3482	29.46	4005	Circuit opened

Table 9

Results of Time-Temperature and Immersion Depth Data on ACL Thermocouple Assembly No. 4735-007

Immersion Depth (in.)	Mean Cavity Temperature (°F)	Measured Cavity Temperature (°F)	Maximum Thermoelectric Output (mv)	Time to Reach Maximum Output (sec)
1/2	2000	1960	3.8	120
1/2	2000	1970	4.3	120
1/2	2500	2645	15.1	70
1/2	3000	2950	19.5	60
1/2	3000	2960	19.5	60
7/8	2000	1935	7.5	80
7/8	2000	1930	7.7	80
7/8	2500	2530	16.0	55
7/8	2500	2535	16.3	54
7/8	3000	2925	22.8	37
7/8	3000	2920	22.2	42
7/8	3000	2875	21.9	42
1 1/4	2000	1940	10.7	55
1 1/4	2000	1945	10.9	55
1 1/4	2500	2530	17.9	46
1 1/4	2500	2490	17.8	46
1 1/4	3000	3005	24.5	34
1 1/4	3000	3015	24.6	36

Table 10

Evaluation of ACL Thermocouple Assembly No. 4735-007
During Repeated Exposures in the Oxy-Acetylene Burner

Exposure	Distance From Burner Face (in.)	Maximum Thermocouple Output (mv)	Temperature Observed on Probe Tip (°F)	Remarks
1	8 7/16	--	2618	Thermocouple Leads Grounded to Sheath
2	8 7/16	24.0	2690	
3	8 7/16	24.3	2728	
4	8 7/16	23.7	2678	
5	5 9/16	23.9	2536	Sight Tube Moved during Exposure
6	5 9/16	26.2	2830	
7	5 3/4	28.6	2976	
8	5 3/4	29.3	3067	Something Appeared to be Melting
9	1 7/8	28.9	3172	Sight Tube too high on Probe Tip
10	1 7/8	29.6	3121	
11	1 7/8	30.0	3150	
12	1 7/8	31.1	3218	
13	1 7/8	31.0	3203	
14	5/8	31.3	3525	Probe Tip Stuck to Sight Tube. Tip Broken in Attempt to Free from Sight Tube

Table 11

Evaluation of ACL Thermocouple Assembly No. 4735-011
During Repeated Exposures in the Oxy-Acetylene Burner

Exposure	Distance From Burner Face (in.)	Maximum Thermocouple Output (my)	Temperature Observed on Probe Tip (°F)	Remarks
1	6	24.7	2761	
2	6	24.8	2965	
3	4	28.5	3325	
4	4	27.3	3115	
5	4	28.5	3070	
6	4	29.0	3152	
7	2	27.1	3065	
8	2	28.3	3100	
9	1/2	40.0	4110	Flame Penetrated Graphite Cavity
10	1/2	34.4	3957	Wall of Cavity Collapsed
11	1/4	41.5	4510	Wall of Cavity Collapsed